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Sofiane Djebarri[1,2], Mohamed Benbouzid[2], Jean Frédéric Charpentier[1] and Franck Scuiller[1]

Abstract–*This research note deals with performance comparison of axial flux modular podded generators for marine current turbines (MCTs). Due to the submarine environment, maintenance operations are very hard, very costly, and strongly depending on sea conditions. In this context, the drive train reliability is a key feature for MCTs. For that purpose, a comparative study is proposed, to assess modular axial flux permanent magnet (AFPM) machines potential for reliability improvement. Thereby, designs of direct-drive modular AFPM generators for a given experimental MCT are performed. The proposed study shows that a pair number of spatially shifted AFPM machine modules, adequately associated, leads to the reduction of the electromagnetic torque ripples transmitted to the MCT shaft. Moreover, it is shown that the proposed module-based generator configuration achieves better thermal behavior. As the actives parts masses and costs are expected to be higher, compromises should be carried-out in terms of reliability and fault-tolerance.*

Keywords: *Marine current turbine, axial flux permanent magnet generator, design, optimization.*

Nomenclature

MCT	=	Marine Current Turbine;
AFPM	=	Axial Flux Permanent Magnet.

I. Introduction

Marine energy has become an issue of significant interest achieving a spectacular increase in the last years. It is currently the focus of much industrial and academic research around the world [1-2]. Indeed, the astronomic nature of this resource makes it predictable, to within 98% accuracy for decades, and independent of prevailing weather conditions. This predictability is critical to a successful integration of renewable energy in the electrical grid. Nevertheless, several marine energy projects over the world are facing difficulties delaying their complete achievement. These difficulties mainly concern installations high-cost and maintenance [3]. Marine current turbines are similar in many aspects to wind turbine technologies. However, because of tide low speeds and to avoid blade cavitations, the turbine rotational speed is typically below 50rpm. For conventional industrial generators, the rated speed is typically between 1000 and 3000 rpm. The use of multistage gearboxes is therefore needed. Such gearboxes lead to low drive train efficiency and high maintenance requirements. To make tidal current energy conversion economically interesting, Marine Current Turbines (MCTs) will need to have an approximately 30 year lifespan with maintenance inspections every 5 years [4]. Therefore, MCTs should be highly efficient and reliable.

Direct-drive permanent magnet generators appear as a solution that can fulfill these specific requirements [5-6]. However, the generator active parts mass and cost are expected to be higher if compared with more conventional high speed industrial generators [7]. In other hand, direct-drive permanent magnets generators are characterized by high torque ripples (around 10% of the rated electromagnetic torque); these ripples can be reduced using a fractional winding distribution. However, this makes the winding manufacturing harder.

In this research note, the focus is on the optimal design and the spatial arrangement of modular AFPM generators in order to reduce the electromagnetic torque ripples (Fig. 1) [8]. Respectively, one, two, and four modules are optimally designed and compared in terms of actives parts costs and masses, and torque ripple on the turbine shaft. In this context and regarding MCTs design, a POD topology seems more favorable than a rim-driven one to achieve multi-module arrangements. For illustration, Fig. 2 shows some of the relevant podded marine current turbine projects [9-10].

II. Design Tools and Methodology

II.1. Design Specifications

The proposed study is based on the specification of a real MCT (300kW) [10-11]. Table 1 gives the specification parameters set used in the design optimization process.

II.2. AFPM Generator Modeling

The AFPM generator geometry is modeled as its equivalent linear machine developed at mean radius. Figure 3 shows the geometry parameters.

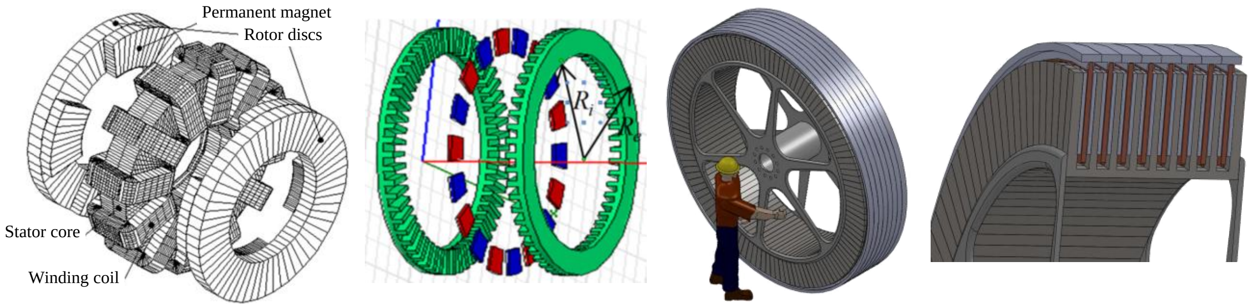

Fig. 1. Examples of axial flux permanent magnet machine concept [8-10] (Illustration reproduced with the kind permission of the authors [8]).

(a) Alstom/TGL turbine [©Alstom]. (b) Voith turbine [©Voith]. (c) Atlantis turbine [©Atlantis].

Fig. 2. Relevant example of podded marine current turbines.

Table 1. DESIGN SPECIFICATION SET.

Turbine radius (Seaflow)	R_0	5.5	m
Torque transmitted by the turbine	Q	191	kNm
Turbine speed	N	15	rpm
Magnet to pole width ratio	β_m	0.65	-
Slot fill factor	k_f	0.65	-
Machine electrical frequency	f_{mach}	50	Hz
Electrical angle	ψ	0	rad
Phases number	m	3	-
Slot number per pole per phase	S_{pp}	1	-
Magnet coercive field	H_{cj}	10^6	A/m
Magnet remanent flux density	B_r	1.2	T
Maximum magnetic flux density in the iron sheets	B_{sat}	1.4	T
Conductors maximum temperature	T_{max}	100	°C
Sea water temperature	T_{water}	30	°C

The AFPM generator electromagnetic modeling is based on an analytical solving of Maxwell equations by variable separation. Then the electromagnetic field is calculated in the permanent magnets and the air gap regions by considering the equivalent slotless machine. This machine is developed by adding a carter coefficient as shown in Fig. 4.

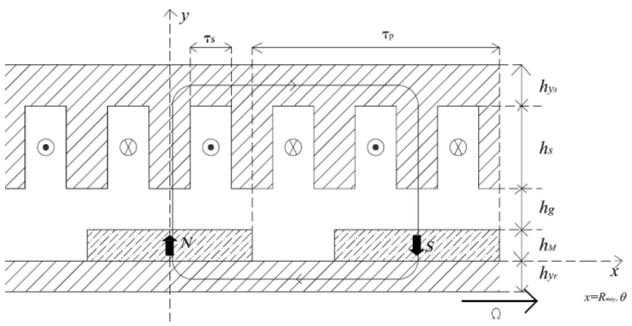

Fig. 3. AFPM generator geometry.

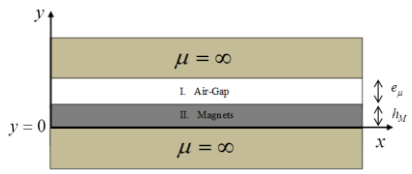

Fig. 4. AFPM generator model representation.

The magnetic field is calculated by solving the following equations [12].

$$\begin{cases} \dfrac{\partial^2 A_z(x,y)}{\partial x^2} + \dfrac{\partial^2 A_z(x,y)}{\partial y^2} = 0 \\ \text{in the air gap (region I)} \\ \dfrac{\partial^2 A_z(x,y)}{\partial x^2} + \dfrac{\partial^2 A_z(x,y)}{\partial y^2} = -\mu_0 \dfrac{\partial M_y(x)}{\partial x} \\ \text{in the permanent magnets (region II)} \end{cases} \quad (1)$$

II.3. Optimization Problem

The optimization objective is to minimize the total cost of the active parts denoted $C(x)$. $C(x)$ is calculated by considering the machine active parts weight described by vector x. Considering this vector; it is possible to define all the AFPM generator geometry [11]. Relation (2) summarizes the optimization problem.

$$\begin{cases} x^* = \min\limits_{x \in X} \left\| C(x) \right\| \\ T_c(x) \le T_{C\max} \\ H_{c\max}(x) \le H_{cj} \\ \eta_{elec} \ge \eta_{elec_{\min}} \\ R_e \le R_{e\max} \end{cases} \quad (2)$$

Where x is the vector defining the optimization variables:

$$x = \begin{bmatrix} B_{g\max} & A_L & J & p & R_e \end{bmatrix}^T$$

The generator external radius is constrained by R_{emax} (set to 1/3 of the turbine radius).

III. Design Results

Table 2 gives the design results of one AFPM optimization. This generator is sized for the 300kW rated power of the turbine. In Table 3, the AFPM generator is optimized for the turbine ½ power (150kW). To fulfill the turbine power specifications, two modules containing each one a 150kW AFPM machine are linked to the MCT. In Table 4, the AFPM machine is optimized for the ¼ rated power of the MCT (75kW). To fulfill the turbine power specification four modules containing each one a 75kW AFPM generator are linked to the MCT.

Figure 5 illustrates the comparison of the total active parts masses and costs, generator maximum temperature, and the torque-to-mass ratio of the different optimized AFPM generators. This figure obviously shows that the AFPM generators modular topology leads to active parts masses and costs oversizing. However for a modular integration, the generator thermal behavior is improved.

In direct-drive permanent magnet machines, the torque ripple is very high (tens of kNm).

Table. 2. DESIGN PARAMETERS
OF A 300KW 1-MODULE AFPM GENERATOR.

300kW AFPM Generator			
Current density	J	4.5	A/m^2 rms
Electrical load	A_L	120000	A/m rms
Air gap flux density	B_{gmax}	0.5	T
Pole pairs poles number	p	120	-
Inner radius	R_i	1.82	m
Outer radius	R_e	2	m
Generator ring thickness	ΔR	17.91	cm
Mean radius	R_m	1.91	m
Magnet to pole width ratio	β_m	66	%
Teeth pitch ratio	β_t	52	%
Rotor yoke thickness	h_{Yr}	0.86	cm
Stator yoke thickness	h_{Ys}	0.86	cm
Slot height	h_s	8.5	cm
Magnets thickness	h_M	0.73	cm
Air gap (magnet/stator)	h_g	0.76	cm
Copper maximum temperature	T_{cmax}	70	°C
Electrical efficiency	η_{elec}	90	%
Magnets maximum magnetic field	H_{max}	0.62	MA/m
Active parts total mass	*Mass*	1840	kg
Active parts total cost	*Cost*	11.7	k€
Torque/active parts mass	$T_{EM}/Mass$	104	Nm/kg

Table. 3. DESIGN PARAMETERS
OF A 150KW 2-MODULES AFPM GENERATOR.

150kW AFPM Generator			
Current density	J	3.5	A/m^2 rms
Electrical load	A_L	120000	A/m rms
Air gap flux density	B_{gmax}	0.45	T
Pole pairs poles number	p	144	-
Inner radius	R_i	1.79	m
Outer radius	R_e	1.9	m
Generator ring thickness	ΔR	10	cm
Mean radius	R_m	1.84	m
Magnet to pole width ratio	β_m	66	%
Teeth pitch ratio	β_t	46.4	%
Rotor yoke thickness	h_{Yr}	0.62	cm
Stator yoke thickness	h_{Ys}	0.62	cm
Slot height	h_s	9.8	cm
Magnets thickness	h_M	0.63	cm
Air gap (magnet/stator)	h_g	0.74	cm
Copper maximum temperature	T_{cmax}	68	°C
Electrical efficiency	η_{elec}	90	%
Magnets maximum magnetic field	H_{max}	0.61	MA/m
Active parts total mass	*Mass*	1200	kg
Active parts total cost	*Cost*	7.25	k€
Torque/active parts mass	$T_{EM}/Mass$	80	Nm/kg

Table. 4. DESIGN PARAMETERS
OF A 75KW 4-MODULES AFPM GENERATOR.

75kW AFPM Generator			
Current density	J	3	A/m^2 rms
Electrical load	A_L	80000	A/m rms
Air gap flux density	B_{gmax}	0.45	T
Pole pairs poles number	p	129	-
Inner radius	R_i	1.6	m
Outer radius	R_e	1.7	m
Generator ring thickness	ΔR	10	cm
Mean radius	R_m	1.65	m
Magnet to pole width ratio	β_m	66	%
Teeth pitch ratio	β_t	42.7	%
Rotor yoke thickness	h_{Yr}	0.57	cm
Stator yoke thickness	h_{Ys}	0.57	cm
Slot height	h_s	7.2	cm
Magnets thickness	h_M	0.55	cm
Air gap (magnet/stator)	h_g	0.66	cm
Copper maximum temperature	T_{cmax}	49	°C
Electrical efficiency	η_{elec}	90	%
Magnets maximum magnetic field	H_{max}	0.596	MA/m
Active parts total mass	*Mass*	770.4	kg
Active parts total cost	*Cost*	5.04	k€
Torque/active parts mass	$T_{EM}/Mass$	62	Nm/kg

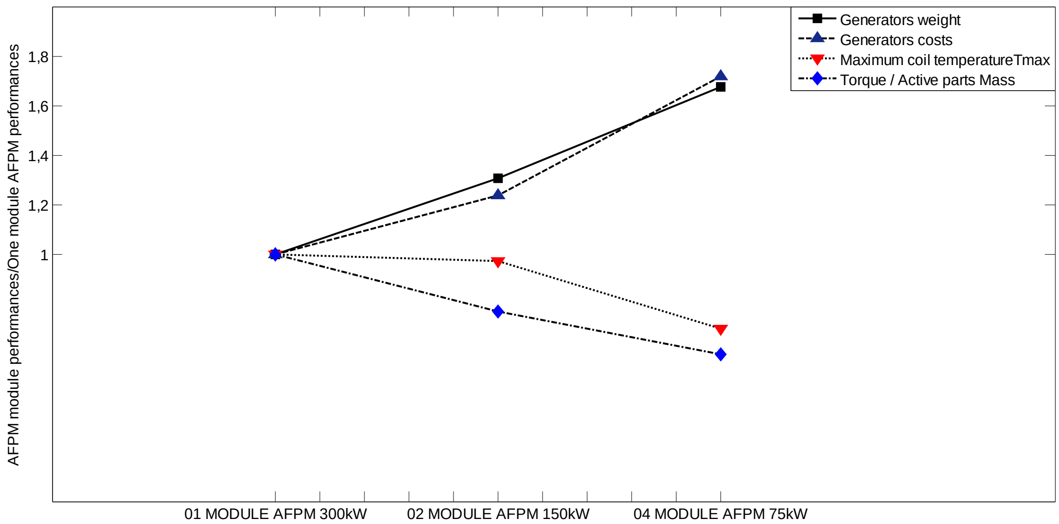

Fig. 5. Modular axial flux generators comparison.

To decrease or even eliminate these ripples, an even number modular arrangement should be considered. In addition, each module is shifted by a specifically mechanical angle (i.e. $\delta = k\pi/6p$ or an integral windings distribution and k is an integer). Figure 6 illustrates therefore the electromagnetic torques of a 1-module 300 kW AFPM generator and a 2-module 150kW AFPM generators.

IV. Conclusion

This research note has proposed a comparative study of a modular structure of axial flux generators that have been optimized to be inserted in a POD to be directly driven by an MCT. Preliminary results show that, apart from improving the MCT thermal behavior, modular arrangements lead to a significant decrease of the turbine torque ripples if the modules are adequately spatially shifted. However, it has been shown that the modular integration leads to actives parts masses and costs oversizing. In this context, compromises should be carried-out in terms of reliability and fault-tolerance.

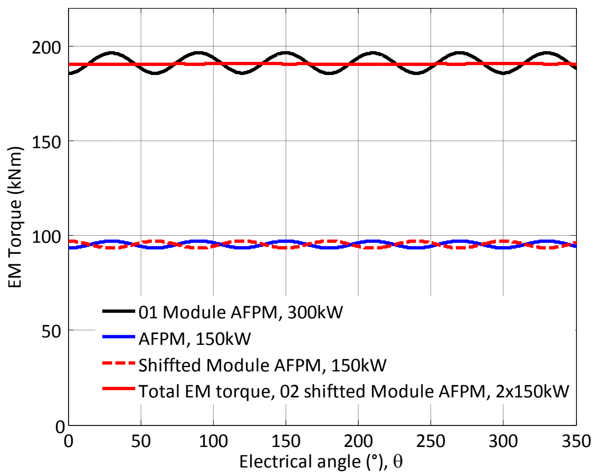

Fig. 6. Electromagnetic torque comparisons.

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